The Discovery and Character of Pleistocene Calcrete Uranium Deposits in the Southern High Plains of West Texas, United States

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U.S. Department of the Interior
U.S. Geological Survey

Cover. Uranium mineralization (yellow) in calcrete sedimentary rocks at the Sulphur Springs Draw uranium deposit, Martin County, west Texas.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	metric ton (t)
	Density	
cubic foot per short ton ($ft^{3/short\ ton}$)	0.0312	cubic meter per metric ton (m^3/t)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
	Mass	
metric ton (t)	1.102	ton, short [2,000 lb]
metric ton (t)	0.9842	ton, long [2,240 lb]
	Concentration	
microgram per liter (µg/L)	1.0432×10^{-9}	ounce per fluid ounce (oz/fl. oz)

Supplemental Information

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L). Results for measurements of stable isotopes of an element (with symbol E) in water, solids, and dissolved constituents commonly are expressed as the relative difference in the ratio of the number of the less abundant isotope (^{i}E) to the number of the more abundant isotope of a sample with respect to a measurement standard.

Abbreviations

Al	aluminum
$^{40}Ar/^{39}Ar$	argon-argon radiometric dating method
As	arsenic
Ba	barium
^{14}C	carbon-14 isotope
Ca	calcium
Cu	copper
DOD	U.S. Department of Defense
EDS	energy-dispersive X-ray spectroscopy
EPA	U.S. Environmental Protection Agency
Fe	iron
H_2O	water
K	potassium
ka	kilo-annum (thousand years ago)
Li	lithium
Mg	magnesium
Mn	manganese
Mo	molybdenum
Mt	million metric tons
P	phosphorus
Pb	lead
ppm	parts per million
SEM	scanning electron microscope
Sr	strontium
Th	thorium
U	uranium
U_3O_8	uranium oxide
USGS	U.S. Geological Survey
V	vanadium
wt%	weight percent
Zn	zinc
Zr	zirconium

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Abstract

This report describes the discovery and geology of two near-surface uranium deposits within calcareous lacustrine strata of Pleistocene age in west Texas, United States. Calcrete uranium deposits have not been previously reported in the United States. The west Texas uranium deposits share characteristics with some calcrete uranium deposits in Western Australia—uranium-vanadium minerals hosted by nonpedogenic calcretes deposited in saline lacustrine environments.

In the mid-1970s, Kerr-McGee Corporation conducted a regional uranium exploration program in the Southern High Plains province of the United States, which led to the discovery of two shallow uranium deposits (that were not publicly reported). With extensive drilling, Kerr-McGee delineated one deposit of about 2.1 million metric tons of ore with an average grade of 0.037 percent U_3O_8 and another deposit of about 0.93 million metric tons of ore averaging 0.047 percent U_3O_8.

The west-Texas calcrete uranium-vanadium deposits occur in calcareous, fine-grained sediments interpreted to be deposited in saline lakes formed during dry interglacial periods of the Pleistocene. The lakes were associated with drainages upstream of a large Pleistocene lake. Age determinations of tephra in strata adjacent to one deposit indicate the host strata is middle Pleistocene in age.

Examination of the uranium-vanadium mineralization by scanning-electron microscopy indicated at least two generations of uranium-vanadium deposition in the lacustrine strata identified as carnotite and a strontium-uranium-vanadium mineral. Preliminary uranium-series results indicate a two-component system in the host calcrete, with early lacustrine carbonate that was deposited (or recrystallized) about 190 kilo-annum, followed much later by carnotite-rich crusts and strontium-uranium-vanadium mineralization in the Holocene (about 5 kilo-annum). Differences in initial $^{234}U/^{238}U$ activity ratios indicate two separate, distinct fluid sources.

Introduction

In the mid-1970s, Kerr-McGee Corporation (hereafter Kerr-McGee) conducted a regional uranium exploration program in the Southern High Plains province of the United States (fig. 1). Its extensive exploration and drilling project led to the discovery and detailed delineation of two near-surface uranium deposits within Pleistocene-age strata of calcareous saline lake sediments. These uranium deposits are located near Big Spring, Texas: the Buzzard Draw deposit is about 25 kilometers (km) to the north-northwest, and the Sulphur Springs Draw deposit is 50 km to the northwest (fig. 2). The deposits were found within privately owned lands (and remain so) and were explored and drilled through lease agreements. Based on more than 900 total drill holes in both deposits, the Sulphur Springs Draw deposit was estimated to contain about 2.1 million metric tons (Mt) of ore with an average grade of 0.037 percent U_3O_8 and the Buzzard Draw deposit about 0.93 Mt of ore averaging 0.047 percent U_3O_8 (table 1; data from Kerr-McGee internal company memorandum).

In 1981, Kerr-McGee conducted an economic analysis to estimate the total costs of developing the two deposits, from mining, transportation, and milling costs through the production of yellowcake (milled uranium oxide). The shallow depth of the deposits, covered by no more than 20 meters (m) of unmineralized rock (overburden), and the soluble nature of the deposits (hosted in calcrete) made them potentially attractive for small-scale open-pit mining. However, the results of the complete economic analysis indicated marginal profitability in an uncertain uranium market, which dissuaded Kerr-McGee from developing these deposits. Its exploration program in this region ended soon after and they released no information on the discoveries and the nature of these deposits was not reported in the published literature.

By the time Kerr-McGee ceased operations for uranium exploration in this region, it had compiled a substantial collection of records from its exploration and drilling

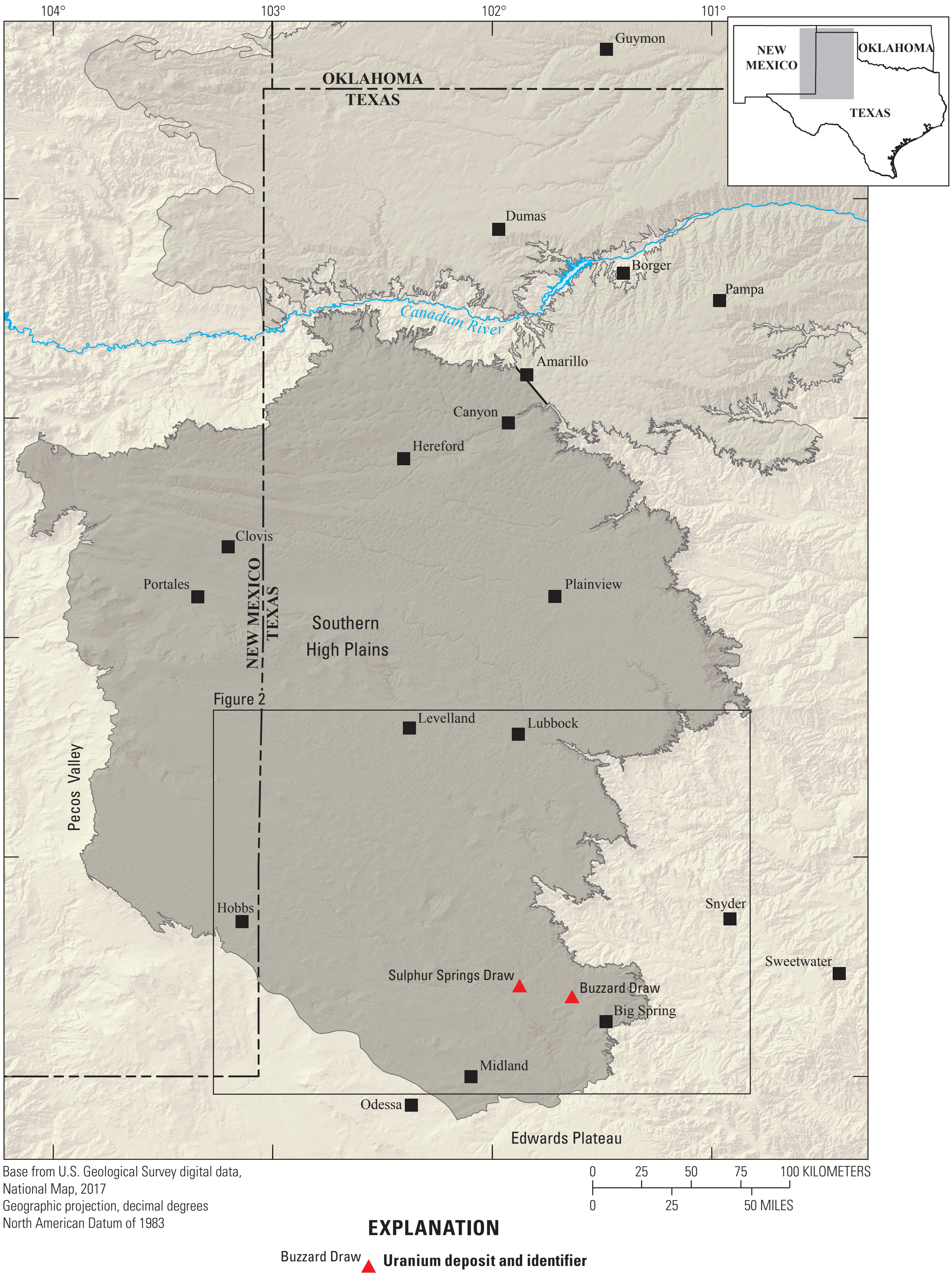
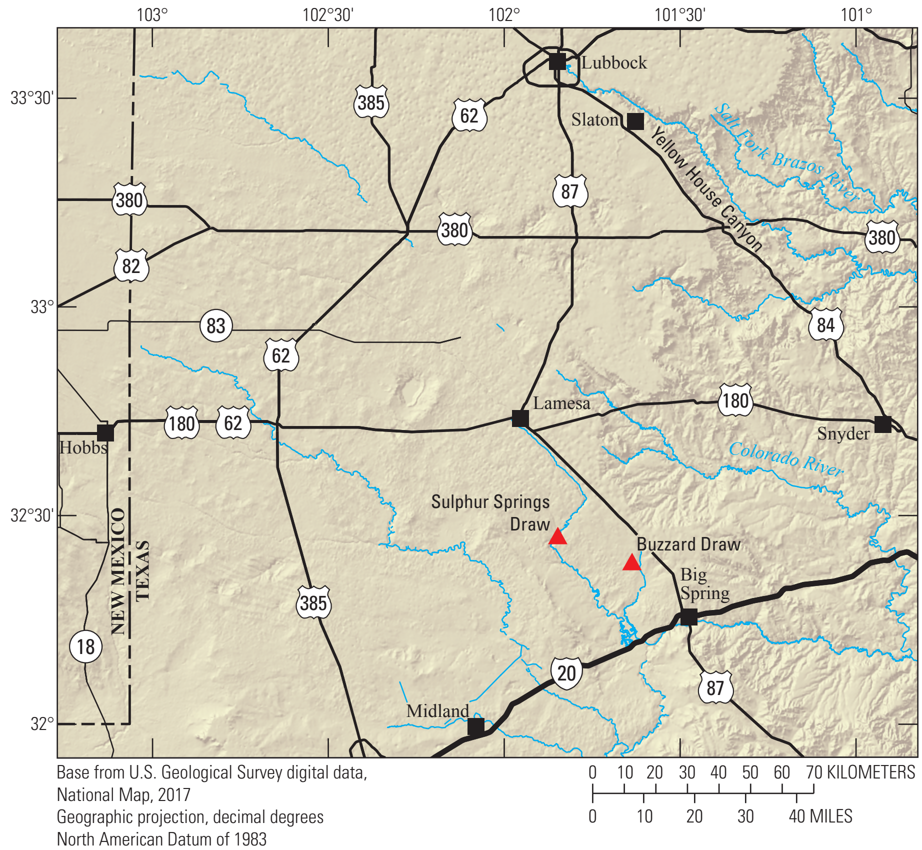


Figure 1. Index map of the Southern High Plains province showing the location of two uranium deposits discovered in the southeast part of the region: the Sulphur Springs Draw and Buzzard Draw deposits.



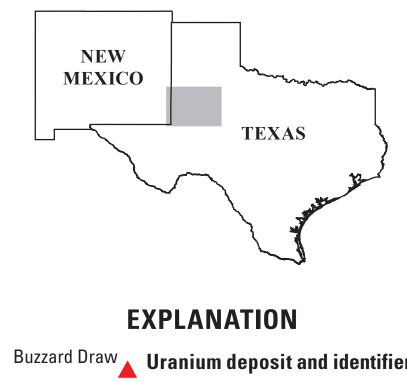


Figure 2. Map showing the location of the Sulphur Springs Draw and Buzzard Draw uranium deposits discovered by Kerr-McGee Corporation in the mid-1970s.

Table 1. Reported ore tonnages and grades in the Sulphur Springs Draw and Buzzard Draw uranium deposits, west Texas, as stated in a Kerr-McGee Corporation company memorandum dated February 25, 1981.

[1 short ton = 0.9072 metric tons; 1 foot (ft) = 0.3048 meters. Multiply U_3O_8 percent by 0.8480 to obtain uranium percent.]

Location (Texas Land Survey System)	Average ore thickness (ft)	Short tons of ore	U_3O_8 percent	Average depth to ore (ft below surface)
Sulphur Springs Draw deposit				
Block 35, T. 3 N.[1]				
Section 19	5.5	69,888	0.043	12.2
Section 17	6.6	112,250	0.039	24.2
Section 28	3.6	238,396	0.044	60
Section 29 "A"[2]	5.2	132,126	0.028	39
Section 29 "B"[2]	5.4	1,132,595	0.036	45.6
Section 29 "C and D"[2]	4.7	626,004	0.037	64.2
Total		**2,311,259**	**0.037**	
Buzzard Draw deposit				
Block 33, T. 2 N.[3]				
Section 19	4.1	665,606	0.048	37
Sections 18 and 19 combined	3.5	357,735	0.047	40
Total		**1,023,341**	**0.047**	

[1]Approximate center of the deposit is in Section 29 at lat 32.4481ºN., long 101.8608ºW.

[2]The "A," "B," and "C and D" designations for Section 29 refer to vertically stacked ore horizons.

[3]Approximate center of the deposit is in Section 19 at lat 32.3972ºN., long 101.6333ºW.

program in the Southern High Plains region, including company memoranda, reports, maps, cross sections, and drill-hole lithology and gamma-ray logs. These records were later purchased by Uranium Energy Corporation (UEC), who has maintained the files. In 2015, UEC allowed the U.S. Geological Survey (USGS) to view these files and gave permission to photocopy, scan, and publish selected information. In addition to a review of the Kerr-McGee findings, this report provides additional observations of the geologic setting and mineralogy of the deposits, preliminary estimates of the age range of the deposits, and additional discussion of possible geologic and geochemical factors and mechanisms that led to their formation.

Yeelirrie Calcrete Uranium Deposits

Kerr-McGee focused its 1970s uranium exploration program on the Southern High Plains (fig. 1) because it determined that the region's geology, paleogeography, and paleoclimate was similar to the setting of the Yeelirrie deposits, which are large, calcrete uranium deposits that had been recently discovered, in 1972, in a remote area of Western Australia. The Yeelirrie deposits are uraniferous calcrete occurrences hosted by nonpedogenic calcretes and dolocretes deposited in valleys as delta and lacustrine sediments that formed in arid inland regions with low relief (Carlisle, 1978; Butt and others, 1984; Cameron, 1984; Cavaney, 1984; Heath and others, 1984). The primary uranium mineral in the Yeelirrie deposits is carnotite, a potassium-uranium-vanadium mineral ($K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$). The Yeelirrie deposits contain disseminated carnotite hosted by lenticular masses of alluvium and soil cemented by calcium (calcrete) or calcium-magnesium carbonate (dolocrete). The carnotite-bearing layers can be as much as 7 m thick, and usually occur within 20 m of the surface (Carlisle, 1978).

It is important to emphasize that the sheet-like layers of carbonate in the topmost few meters of the Southern High Plains, regionally referred to as "caliche," are related to pedogenic (soil-forming) processes (Reeves, 1976; Holliday, 1989, 1990; Gustavson and others, 1995; Gustavson, 1996). (Although caliche is now more commonly referred to as "soil carbonate" or "pedogenic carbonate" by soil scientists, the term "caliche" is used in this report to follow the common usage in the literature focusing on this region.) Saline lacustrine basins that formed in the Pleistocene and still exist today are scattered across the Southern High Plains, and these often contain lenticular deposits of calcareous, nonpedogenic sediments (calcrete) formed by evaporation of saline lakes (Evans, 1956; Frye and Leonard, 1957, 1968).

Regional Setting

The previously unreported calcrete uranium deposits of west Texas, United States, lie in the southeast part of the Southern High Plains physiographic province (fig. 1). The Southern High Plains, also referred to as the "Llano Estacado" or "Staked Plains" (for example, Frye and others, 1982), generally coincides with the erosional extent of the Ogallala Formation and includes roughly the northern half of the Permian Midland Basin. The province is bounded by caprock escarpments to the east and west and by the Canadian River to the north; to the south, it grades into the Edwards Plateau (fig. 1). Most of the Southern High Plains province is in northwest Texas, but it extends into southeast New Mexico on its western side (Reeves, 1972; Frye and others, 1982). The dominant cap rock in this region is a thick layer of caliche, as much as 5 m thick.

Stratigraphy

Rocks exposed in the Southern High Plains are predominantly flat-lying, Upper Triassic to Holocene sedimentary strata (figs. 3 and 4). The two discovered uranium deposits occur within weakly consolidated, calcareous sediments that were deposited in saline lake environments during the late Pleistocene. The stratigraphy of the Southern High Plains provides insights into the paleogeographic setting and environmental conditions that contributed to the formation of these uncommon uranium deposits.

Upper Triassic Dockum Group

The Dockum Group in the southeastern part of the Southern High Plains is typified by alternating brownish-red and greenish-gray strata of cross-bedded sandstone, clay, sandy to silty shale, and conglomerate (Eifler and others, 1974; McGowen and others, 1979; Frelier, 1987; May, 1988; Murry, 1989). The basal unit is a conglomerate containing chert pebbles, sandstone cobbles, and petrified wood. The Dockum Group has a maximum thickness of about 137 m in the province. The Dockum Group strata represent deposition in fluvial, lacustrine, lacustrine-deltaic, lacustrine-beach, valley-fill environments and paleosols; fluvial deposits are most abundant (McGowen and others, 1979; May, 1988).

Scattered areas within the Dockum Group in west Texas exhibit anomalous radioactivity, 2 to 5 times higher than background, mainly in grayish and greenish strata and in carbonaceous material (Finch, 1975). In the Trujillo Formation, the uppermost formation of the Dockum Group, scattered

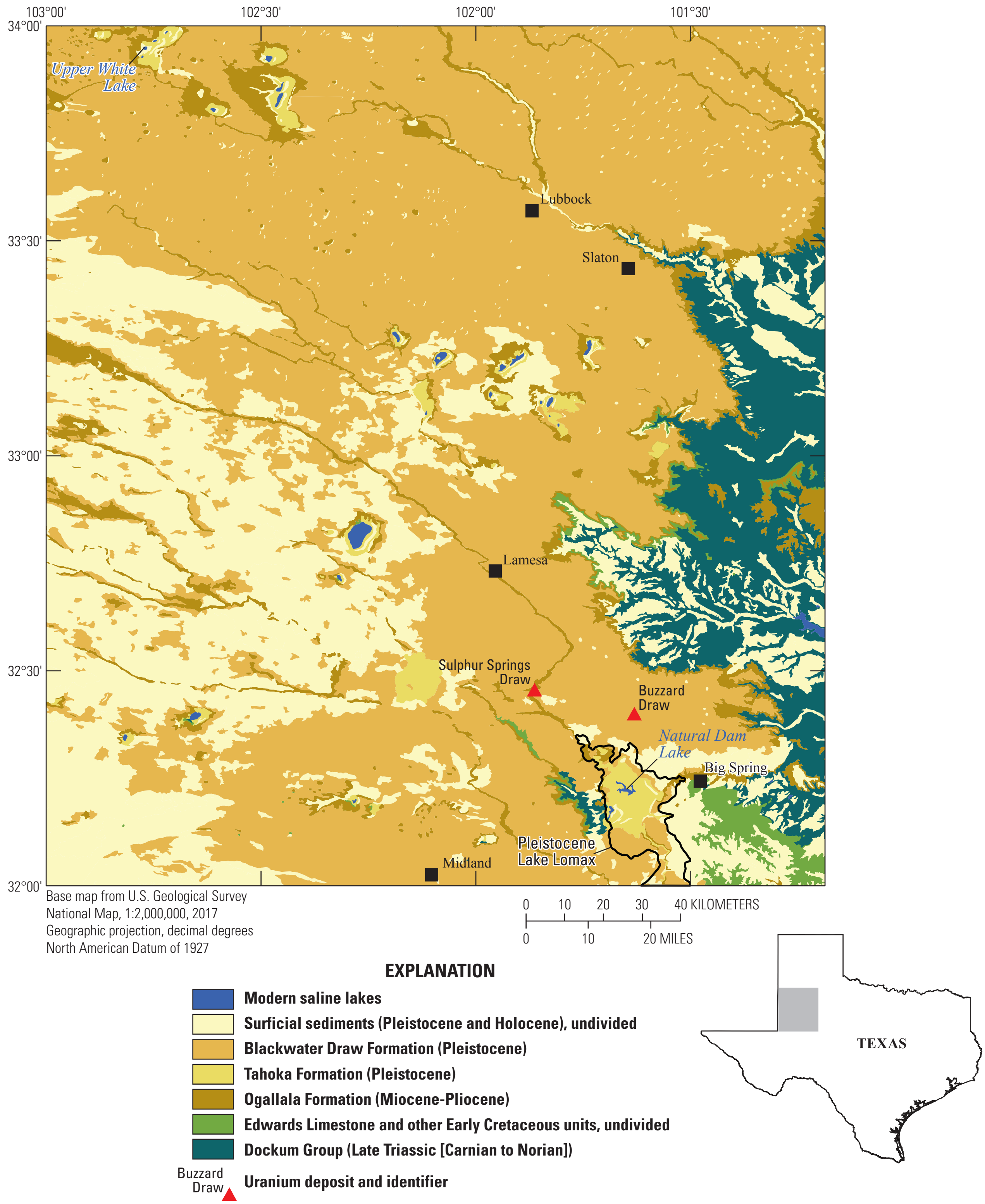


Figure 3. Generalized geologic map of the southeastern area of the Southern High Plains in west Texas. Geology shown is generalized from Barnes and others (1992). Outline of Lake Lomax from Frye and Leonard (1968).

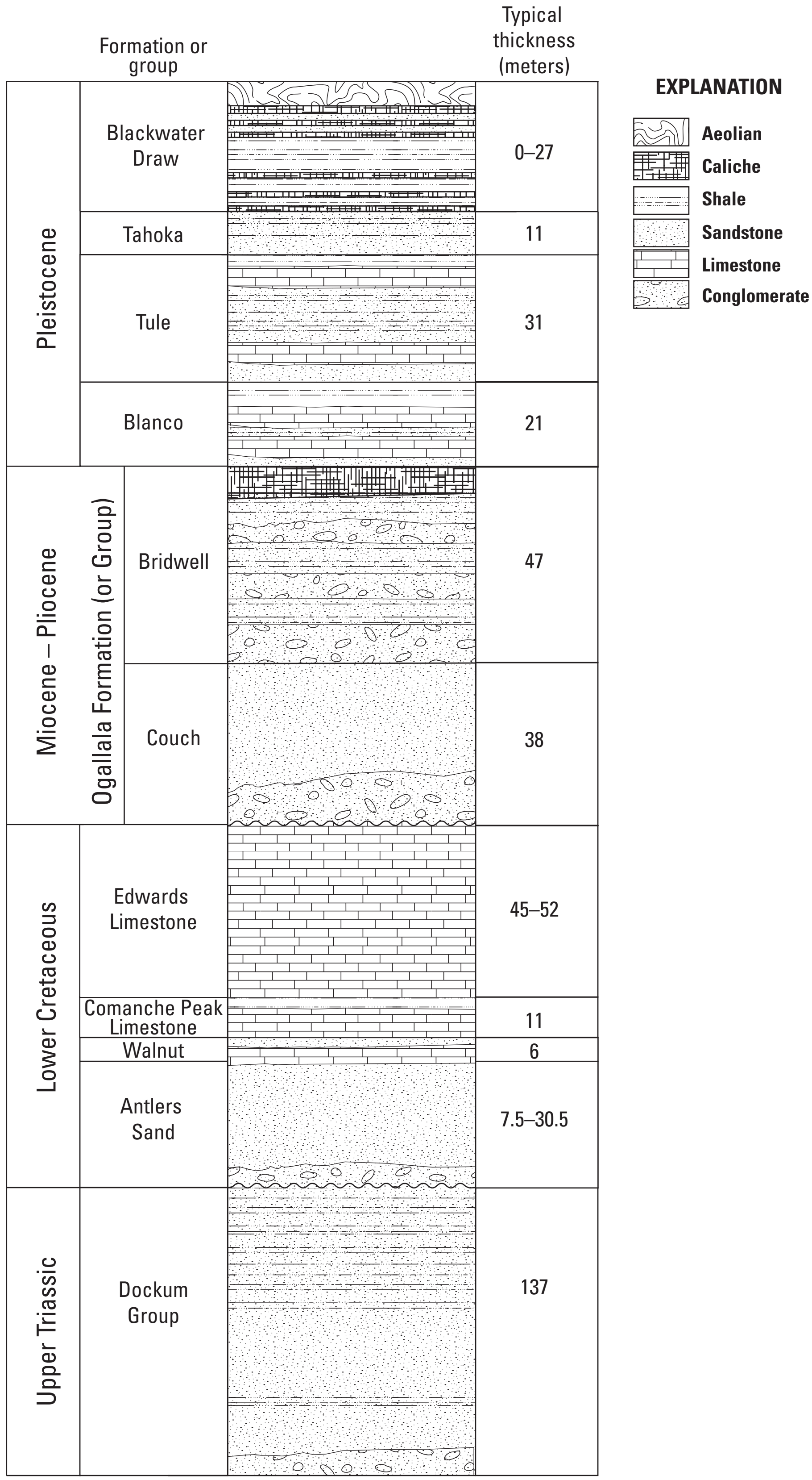


Figure 4. Stratigraphy of the geologic units exposed in the Southern High Plains province showing the units relevant to the geologic setting of the uranium deposits. Stratigraphic information from Evans (1956), Eifler and others (1974), Holliday (1989), and Murry (1989).

lenses of uranium mineralization are no more than 30 centimeters (cm) thick but can be up to 250 m long; they are found in deposits of fluvial channels. The largest identified deposit comprised about 780 short tons (708 metric tons), averaging 0.20 percent U_3O_8 (Finch, 1975). Uranium minerals reported are tyuyamunite, metatyuyamunite, autinite, meta-autunite, bayleyite, liebigite, and cuprosklodowskite (Finch, 1975).

To evaluate the uranium-bearing potential of the Dockum Group, McGowen and others (1977) collected and analyzed the uranium content of more than 400 outcrop samples of the different depositional facies. The majority of their samples were collected in the extensive outcrops of the Dockum Group that are east of the caprock escarpment that extends from the Big Spring region to the Slaton region (fig. 3). About 90 percent of their Dockum samples contained less than 5 parts per million (ppm) U_3O_8. In the fluvial facies, meandering stream deposits had the highest uranium content, mainly in channel lag deposits (high value of 79 ppm U_3O_8 in lag channel with carbonized logs). Lacustrine deposits had the highest uranium contents (with a maximum value of 840 ppm U_3O_8). McGowen and others (1977) concluded that the most favorable Dockum Group strata for uranium occurrences are fluvial, deltaic, and lacustrine facies. McGowen and others (1977, p. 67) further concluded that "one can speculate that most of the uranium that will be found in the Triassic Dockum Group of Texas will be in the channel lag facies."

It is noteworthy that the Pleistocene-age lacustrine strata hosting the two uranium-bearing calcrete deposits described in this report rests directly on the Dockum Group. This is a significant erosional unconformity and indicates that any Lower Cretaceous strata and Miocene–Pliocene Ogallala Formation strata that may have been deposited in these areas was removed prior to the development of Pleistocene lakes.

Lower Cretaceous Formations

Lower Cretaceous rocks exposed in the southern areas of the Southern High Plains include, from oldest to youngest, the Antlers Sand, Walnut Formation, Comanche Peak Limestone, and Edwards Limestone (fig. 4). More detailed descriptions of these units are provided by Eifler and others (1974), the source of the generalized descriptions of the Cretaceous formations that follow.

- The Antlers Sand consists of sandstone, siltstone, and locally quartzite, with a conglomerate unit at its base. The formation ranges from 7.5 to 30.5 m in thickness.
- The Walnut Formation consists of interbedded shale, sand, argillaceous limestone, and marl. Large marine fossils are common. The formation has a maximum thickness of 6 m.
- The Comanche Peak Limestone is layered limestone interbedded with thin shale layers. Large marine fossils are common. The formation is as much as about 11 m thick.
- The Edwards Limestone is massive to thickly bedded limestone, locally dolomitic with chert. The formation ranges from 45 to 52 m in thickness.

Miocene–Pliocene Ogallala Formation

The Miocene–Pliocene Ogallala Formation is the primary groundwater aquifer and source of potable water in the Southern High Plains (Nativ, 1988; Mullican and others, 1997). The Ogallala Formation within the Southern High Plains, sometimes called the "Ogallala Group," consists of alluvial sediments that include coarse gravel, silt, and clay; local interbedded eolian deposits; and buried soil horizons (Gustavson, 1996). The Ogallala sediments were deposited by fluvial processes on a widespread, variably incised erosional surface, spreading in all directions as an alluvial apron across this region during the late Tertiary (Miocene and early Pliocene) (Frye and others, 1982; Reeves and Reeves, 1996). The Ogallala Formation in the Southern High Plains is interpreted as the erosional remnant of an extensive sheet of continental sediments derived from bedrock sources in the southern Rocky Mountains, which was deposited on a mature erosional surface of Cretaceous, Triassic, and Permian rocks. In the Southern High Plains, Ogallala deposits can variably rest directly upon strata of the Triassic Dockum Group or can lie in contact with the eroded surface of Lower Cretaceous rocks (Brand, 1956a). On the upper surface of the Ogallala, well-developed zones of thick-layered caliche (as much as several meters thick) can form the caprock escarpments that define the eastern boundary of the Southern High Plains in Texas and the western boundary in southern New Mexico (Frye and others, 1982).

In the Southern High Plains region, the Ogallala Formation (or Group) is locally divided into two units: the lower Pliocene Couch unit and the overlying middle Pliocene Bridwell unit (Evans, 1956; Winkler, 1985) (fig. 4). Vertebrate fossils in each of the formations reveal the age of each unit. The Couch unit is exposed in washes and escarpments just east of the eastern escarpment of the Southern High Plains (east and southeast of Lubbock) and can lie unconformably on either Triassic or Cretaceous strata. It contains a basal interval of fluvial cross-bedded sands and gravels, which is overlain by an upper member of unstratified, calcareous, clayey sands. The Bridwell unit, which forms the upper parts of the Ogallala in this region, rests unconformably on the Couch unit strata; where the Couch unit is absent, the Bridwell strata rest on Triassic and Cretaceous rocks. Most of the Bridwell unit consists of stratified, unconsolidated clay, with local channel deposits in the upper parts of the formation. The Bridwell strata are interpreted as channel and floodplain sediments deposited by broad, aggrading streams (Evans, 1956; Winkler, 1985).

An alluvial paleochannel of the Ogallala Formation locally known as the "Slaton Channel," about 0.8 km wide and 15.25 to 18.3 m thick, is exposed east of Slaton. The Slaton Channel has been and is currently mined as a source of aggregate (Winn, 2015). This paleochannel is adjacent to an area in Yellow House Canyon (fig. 2) that was drilled by Kerr-McGee in the late 1970s; it was selected for drilling based on radiometric anomalies detected in an airborne survey.

The ancestral Pecos River system spread a vast apron of overlapping and coalescing alluvial sediments, which is preserved as the Ogallala Formation (Wood, 2002). However, in the late Pliocene, because of progressive headward erosion moving northward, the ancestral Pecos River likewise moved northward, where it pirated the channels of the Southern High Plains that previously flowed eastward; this led to the establishment of the routes of the modern Pecos and Canadian Rivers (Reeves, 1972; Gustavson and Finley, 1985; Gustavson and Winkler, 1988). This stream piracy cut off stream flows and fluvial input to the Southern High Plains, ending Ogallala Formation deposition in the region and contributing to the aridity of the plains during much of the period that followed.

Subsequently, shallow valleys ("draws") were cut through the caliche cap of the Ogallala during relatively wet glacial periods and then partly filled with fluvial, eolian, and lacustrine deposits during relatively dry interglacial periods (Frye and Leonard, 1968; Holliday, 1995). Within the Ogallala and overlying Blackwater Draw Formations, numerous calcic horizons indicate periods when evapotranspiration exceeded precipitation, resulting in the precipitation and formation of calcium carbonate (caliche layers) under arid to semiarid conditions (Gustavson and Winkler, 1988; Holliday, 1995; Gustavson, 1996; Gustavson and Holliday, 1999).

Lower Pleistocene Blanco Formation

The type section for the Blanco Formation is at "Mount Blanco," a small white hill located about 60 km northeast of Lubbock and 14.5 km north of Crosbyton, Tex. (at lat 33.79139ºN., long 101.25306ºW.). The Blanco Formation, composed of light gray, bentonitic clay, sand, freshwater limestone, and ash layers, was deposited locally in an early Pleistocene basin in lacustrine environments on the upper surface of the Pliocene Ogallala Formation (Evans, 1956; Holliday, 1988). An abundance of diagnostic vertebrate fossils indicates that the Blanco Formation is early Pleistocene in age. Based on an interbed of the Guaje Ash at the type section, Holliday (1988) concluded that deposition of the Blanco sediments ended about 1.6 Ma or earlier. Ash layers, such as those in the Blanco Formation, are rare and not widespread in the Southern High Plains.

Middle Pleistocene Tule Formation

The strata of the Tule Formation are lacustrine deposits similar to those of the Blanco Formation. The type locality of the Tule Formation is about 110 km north-northeast of Lubbock, Tex.; similar deposits (that are likely equivalent) also occur in Yellow House Canyon, east of Slaton (Evans, 1956). The Tule Formation consists mainly of bentonitic clay interbedded with medium- to fine-grained sand and a thin zone of freshwater limestone. Margins of the formation locally contain gravel and layers of volcanic ash resting on Pliocene rocks (Ogallala Formation; Evans, 1956; Schultz, 1986). The basin that hosts the Tule deposits is over 11 km long and elongate in an east-west orientation (Evans, 1956). In the center of the basin, Tule Formation rocks lie unconformably on Triassic red beds (Dockum Group).

Upper Pleistocene Tahoka Formation

The strata of the Tahoka Formation consist of weakly coherent, friable layers of clay, silt, and fine-grained sand, locally calcareous and gypsiferous, that are interpreted as lacustrine sediments deposited during the Wisconsinan period (Frye and Leonard, 1957; Hall, 2001; Wood, 2002; Rich, 2013). In some areas, fine-grained facies of the formation laterally grade to gravel deposits. The Tahoka Formation is best exposed in the rims of approximately 30 large saline lakes of the Southern High Plains (Goolsby, 1975) (fig. 3).

A geochronology and paleoenvironmental study by Hall (2001) used radiocarbon ages of organic matter as well as pollen analysis of Tahoka Formation strata at Upper White Lake, a saline lake about 115 km northwest of Lubbock (fig. 3). Hall's study identified several periods of lake filling between 20,000 and 17,000 ^{14}C years before present, during the last glacial maximum (late Wisconsinan). He suggests possible drying of the lake by 14,000 ^{14}C years before present (Hall, 2001).

Wood (2002) reported ages of tufa layers in the Tahoka Formation on the banks of Double Lakes, Tex., as late Wisconsinan. The lower strata were revealed to have been deposited approximately 51 kilo-annum (ka) by a 3-m-thick tufa at Double Lake; the middle section was dated at 42 ka, and the upper meter was dated at approximately 24 ka.

Pleistocene Lacustrine Deposits that Host the Uranium Deposits

Calcareous sediments that were likely deposited in saline lakes are the host strata for the Sulphur Springs Draw and Buzzard Draw uranium deposits. These lakes probably formed during dry interglacial periods when evaporation exceeded water supply in the region. In the exploration model employed by Kerr-McGee, the lacustrine strata that host the Sulphur Springs Draw and Buzzard Draw uranium deposits were genetically associated with a large Pleistocene lake located downstream to the south. This large saline lake has been named "Lake Lomax." It is the largest Pleistocene lake identified in the Southern High Plains region and is located near the southeastern edge of the province, just west of Big Spring, Tex. (fig. 3). As defined by Frye and Leonard (1968), the lake basin is at least 40 km in length and elongate, trending west-northwest to south-southeast (fig. 3). Lacustrine sediments composed of fine- to medium-grained sand and gypsum grains interbedded with silt and minor clay define the extent of Lake Lomax (Frye and Leonard, 1968). Modern saline lakes west of Big Spring, such as Natural Dam Lake (fig. 3), may represent evaporating remnants of Lake Lomax.

Frye and Leonard (1968) reported that upper parts of Lake Lomax strata contain early Wisconsinan molluscan faunas (late Pleistocene), while lower, non-fossiliferous strata of this lake basin may date to the Illinoian. Frye and Leonard (1968) stated that no evidence exists to indicate that a large lake basin existed in the area during the Pliocene, the time of deposition of the upper strata of the Ogallala Formation. They interpret that Lake Lomax ultimately drained through an outlet that formed west of Big Spring, Tex. A detailed model for the formation, lake-level fluctuations, and ultimate draining of Lake Lomax is described by Frye and Leonard (1968).

The chronostratigraphic relationship between the uranium-bearing lacustrine strata, the Tahoka Formation, and the former Lake Lomax remains uncertain. At most of its exposures in the region, the Tahoka Formation rests on alluvial sediments of the Miocene–Pliocene Ogallala Formation. In contrast, in the Sulphur Springs Draw and Buzzard Draw deposits, the uranium-bearing lacustrine strata lie directly on red-bed siltstones and sandstones of the Triassic Dockum Group.

As part of this USGS study, we sampled strata immediately adjacent to the Sulphur Springs Draw deposit. One sample revealed a thin (2 cm thick) tephra layer composed of glass shards coated with clay (sample location at lat 32.45244ºN., long -101.86386ºW.). Age determinations of this ash layer by the USGS Tephrochronology Project determined that this ash was Lava Creek B with an age of 631±4 ka ($^{40}Ar/^{39}Ar$ method, Fish Canyon standard, 28.17 Ma, Matthews and others, 2015); its eruptive source is in the Yellowstone National Park region of Wyoming. The Lava Creek B ash in this region occurs in the upper part of the Tule Formation (middle Pleistocene), thus suggesting that strata of the Tule Formation are the host for the Sulphur Springs Draw uranium deposit.

Kerr-McGee's internal geologic reports suggest that the Pleistocene lacustrine complexes that are underlain by Triassic red beds of the Dockum Formation are the settings found to host the strongest uranium mineralization discovered thus far, as exemplified by both the Sulphur Springs Draw and Buzzard Draw deposits. In some areas of the Southern High Plains, Cretaceous strata directly underlie the Pliocene sedimentary deposits. However, in the region with the two known uranium deposits, Brand (1956b) showed that in most of the area Triassic rocks directly underlie the Pliocene strata (Ogallala Formation) and that Cretaceous strata are absent.

Quaternary Blackwater Draw Formation and Holocene Sediments

Transitioning from the late Pleistocene to the middle Holocene, the hydrology of the Southern High Plains region shifted from flowing streams to almost entirely standing water because of a significant climate change that decreased precipitation across the region (Holliday, 1995). Less surface and groundwater input led to the development of extensive eolian environments across the region. Wind deflation of the exposed Southern High Plains surface resulted in eolian deposits.

The Quaternary Blackwater Draw Formation covers much of the Southern High Plains of northwestern Texas (fig. 3). The unit consists of eolian sand, silt, and sandy mud interbedded with at least six buried calcareous soil horizons that are each 1–2 m thick (Holliday, 1989; Gustavson, 1996; Gustavson and Holliday, 1999). Studies suggest that accumulation of the soil layers occurred during periods of prolonged aridity; according to Holliday (1989, p. 1598), "each cycle of sedimentation-stability lasted for several hundred thousand years and that [sic] the last depositional event occurred at least several tens of thousands of years ago." The sediments were subsequently modified by pedogenic processes. Deposition of the formation occurred during much of the Quaternary, as evidenced by interbedded layers of the 0.62-m.y. Lava Creek B ash and the 1.61-m.y. Guaje Ash (Holliday, 1989, 1990).

Drainage in the Blackwater Draw Formation, which forms the modern surface of the Southern High Plains, is through numerous small playas. Approximately 20,000 small playa basins have been recognized on the surface of the Southern High Plains (Texas Department of Water Resources, 1980; Gustavson and others, 1995). The playa basins contain ephemeral alkaline lakes that are typically less than 1 km in diameter and no more than 4 m in depth (Wood and Osterkamp, 1984). Interbedding of Blackwater Draw Formation strata and playa sediments suggest that these playa basins formed during the Quaternary (Gustavson and others, 1995).

Several studies incorporating stratigraphic, chemical, and isotopic evidence suggest that recharge of the Ogallala aquifer system occurs mostly through these playas (Scanlon and others, 1994; Gustavson and others, 1995; Wood and Sanford, 1995; Mullican and others, 1997). Although the playas only compose approximately 6 percent of the Southern High Plains, much less recharge occurs in the areas between the playas (Scanlon and others, 1994; Gustavson and others, 1995; Wood and Sanford, 1995; Mullican and others, 1997). By collecting runoff and focusing recharge into the Ogallala aquifer, the playas have a significant role in that they are the primary supply of domestic and agricultural waters to the region (Gustavson and others, 1995).

Holocene surficial units across the Southern High Plains include sedimentary deposits from sand sheets, dune sands, alkali flats, caliche, and playas, as well as ponds, alluvium, and small stream terraces along draws.

Kerr-McGee Corporation's Exploration Program and Discoveries in the Southern High Plains

Early Exploration for Triassic Red-Bed Uranium Deposits

Kerr-McGee's exploration in the region began in the 1960s, with its original focus on the potential for uranium deposits within the Permian-Triassic unconformity in the Midland Basin area, near the eastern escarpment of the Southern High Plains of Texas. In this region, Kerr-McGee adopted a model of potential uranium mineralization in the Triassic Dockum Group strata of the Southern High Plains because of its general lithologic and facies similarities to uranium-bearing red beds and channels of the Triassic Chinle Formation in southeastern Utah and northeastern Arizona (Finch, 1991). Specifically, the uranium potential of the Dockum Group was investigated as an analogue to Lisbon Valley uranium deposits of the Colorado Plateau (Wood, 1968). In the Southern High Plains, Triassic red-bed sedimentary rocks of the Dockum Group (figs. 3 and 4) are considered generally correlative with the Chinle Formation of the Colorado Plateau (McGowen and others, 1979).

In the Midland Basin area of west Texas, Kerr-McGee initially focused on an area in the northeastern part of Garza County, about 65 km east-southeast of Slaton, Tex. (fig. 2), which contains four previously known uranium prospects within Triassic strata of the Dockum Group. Locations and descriptions of these uranium occurrences are provided in Hayes (1956) and Finch (1975). A Kerr-McGee internal report noted that (1) in adjacent Lynn County, directly west of the uranium prospects (an area about 6–8 km south of Slaton, Tex.), gamma-ray anomalies were found in several oil well logs where basal Triassic Dockum Group sandstones reach their maximum thickness and (2) water wells drilled in this same area showed that groundwaters in the same stratigraphic horizon contain anomalously high amounts of uranium and radium. As a result, Kerr-McGee drilled seven prospective areas in Lynn and Terry Counties of west Texas. In a memorandum dated April 5, 1979, Kerr-McGee stated, "Drilling [in these prospects] has been discontinued due to very discouraging results. Only 9 of the 122 holes drilled were anomalous, and none of these exceeded twice background in strength. The rest of the holes were barren." Apparently, these seven prospect areas were selected primarily on the basis of groundwater samples with high uranium concentrations, such as 100–350 parts per billion (ppb). The holes were drilled at quarter-mile to half-mile spacing.

Exploration Program Transition to Yeelirrie Uranium Deposits

In May 1973, Kerr-McGee initiated a new uranium exploration program in the Southern High Plains that shifted its focus towards the potential for surficial uranium deposits similar to the Yeelirrie ore bodies of Western Australia (Carlisle, 1978; Cameron, 1984).

Kerr-McGee's exploration project focused initially on the use of its proprietary ARDA (Airborne Radiometric Detection Apparatus) technique. Its regional airborne radiometric reconnaissance of the Southern High Plains included the extent of Ogallala Formation outcrops from the vicinity of Midland-Odessa in the south to about Amarillo in the north. This airborne reconnaissance survey located several radiometric anomalies near the edge of the Ogallala caprock escarpment along the eastern margin of the Southern High Plains in Texas. These anomalous areas were then inspected on the ground by Kerr-McGee geologists.

A radiometric anomaly reading about 1.5 to 2 times background values was detected by the airborne reconnaissance survey in part of Yellow House Canyon, which is about 10 km east of Slaton, Tex. (fig. 2). A separate aerial radiometric survey over the region during this same time period, flown as part of the U.S. Department of Energy National Uranium Resource Evaluation (NURE) Program (McGowen and others, 1981; Hill and others, 2009), also detected radiometric anomalies within this same area of Yellow House Canyon. This anomalous area was visited by Kerr-McGee geologists, who traced uranium mineralization to conglomeratic channel sandstone thought to be of Ogallala age. Company memoranda indicate that assays of outcrops of conglomeratic sandstone and greenish siltstone revealed concentrations of 0.034 to 0.053 percent U_3O_8. This area was then explored by 27 shallow drill holes, each less than 30 m in depth. Only six of the holes were barren (background radiation levels were detected), but the highest uranium mineralization encountered was 0.028 percent U_3O_8. Based on these results, the short-lived exploration near Slaton was abandoned.

Recent sampling of outcrops in by the USGS in the Yellow House Canyon (this study) near Kerr McGee's anomalous areas found enrichments in uranium and vanadium in strata of the Blanco Formation and the Couch unit (Ogallala Group) (table 2). The highest uranium values were found in a calcareous bed in the upper Blanco Formation (142 ppm uranium) and very fine grained calcareous sandstone in the Couch unit (107 ppm uranium). Samples of a conglomerate bed in the Couch unit also showed anomalous uranium content (67 and 71 ppm uranium). This conglomerate may correspond to the conglomeratic channel sandstone thought to be of Ogallala age, the rock unit identified by Kerr-McGee as the source of airborne radiometric anomalies in this area. In addition to uranium, calcareous clastic sediments of the Couch unit in this area show anomalous concentrations of vanadium (124 to 529 ppm vanadium). The anomalous uranium and vanadium concentrations in calcareous

Table 2. Concentrations of selected elements in samples collected in 2014 and 2015 from outcrops within the general area in which 1970s reconnaissance airborne radiometric surveys flown by Kerr-McGee and the National Uranium Resource Evaluation program detected radiometric anomalies (1.5 to 2 times background). This area is about 10 kilometers east of Slaton, Crosby County, Texas. Samples are presented in stratigraphic order with samples from the youngest strata at the top.

[Datum for latitude and longitude values is World Geodetic System 1984 (WGS84). Al, aluminum; As, arsenic; Ba, barium; Ca, calcium; Cu, copper; Fe, iron; K, potassium; Li, lithium; Mg, magnesium; Mn, manganese; Mo, molybdenum; P, phosphorus; Pb, lead; Sr, strontium; Th, thorium; U, uranium; V, vanadium; Zn, zinc; Zr, zirconium; wt%, weight percent; ppm, parts per million]

Sample	Latitude	Longitude	Formation	Concentration[1]												
				Al wt%	Ca wt%	Fe wt%	K wt%	Mg wt%	Mn wt%	Ba ppm	Li ppm	Sr ppm	U ppm	V ppm	Zn ppm	Zr ppm
USGS–10	33.43332	–101.53155	Blanco	0.53	5.65	0.18	0.36	3.57	0.004	699	20	>10,000	142	31	12	204
USGS–9	33.43340	–101.53175	Blanco	1.12	2.95	0.41	0.69	2.15	0.007	381	20	813	3	33	10	223
05–TX15	33.43319	–101.53231	Blanco	2.21	3.9	1.26	1.1	2.96	0.013	240	37	1,238	14	327	17	162
USGS–8	33.43350	–101.53227	Blanco	1.46	11.1	0.54	0.74	7.11	0.024	348	30	1,140	33	136	18	107
04–TX15	33.43339	–101.53239	Blanco	1.56	7.5	0.48	0.7	4.57	0.013	522	23	741	42	139	9	152
USGS–7	33.43487	–101.52974	Ogallala	0.99	15.9	0.37	0.41	8.18	0.007	245	20	8,700	18	36	14	90
USGS–6	33.43643	–101.53255	Ogallala	0.76	12.2	0.3	0.39	6.63	0.018	361	20	1,860	71	99	8	84
USGS–5	33.43765	–101.53110	Ogallala	0.66	27.9	0.25	0.3	1.34	0.004	342	<10	2,350	3	13	9	67
01–TX15	33.44503	–101.53622	Couch	1.90	5.0	0.75	0.9	0.47	0.011	445	11	135	2	41	9	255
USGS–1	33.44353	–101.53593	Couch	2.96	5.06	1.26	1.32	3.76	0.029	530	30	510	45	522	24	230
03B–TX15	33.44344	–101.53628	Couch	2.76	5.2	1.32	1.2	3.84	0.032	279	29	575	40	529	19	177
USGS–3	33.44353	–101.53593	Couch	0.78	10.7	0.29	0.36	5.94	0.014	146	10	622	107	124	<5	94
USGS–4	33.44146	–101.53536	Couch	0.87	11.7	0.34	0.45	6.51	0.009	249	20	947	72	186	14	46
USGS–2	33.44353	–101.53593	Couch	1.34	6.99	0.45	0.79	3.92	0.053	2,250	10	737	67	403	10	56
03A–TX15	33.44344	–101.53628	Couch	1.37	7.3	0.49	0.7	3.99	0.054	2,244	13	692	71	366	6	78
02A–TX15	33.45217	–101.52469	Dockum	2.62	7.3	0.76	0.9	0.37	0.101	223	13	305	2	40	13	139
02B–TX15	33.45217	–101.52469	Dockum	5.94	8.4	2.68	2	1.44	0.122	213	34	637	5	192	49	183

Sample descriptions

USGS–10	Calcareous nodules eroding out of friable calcareous bed; upper Blanco Formation.
USGS–9	Slightly calcareous, very fine grained sandstone; apparently Blanco Formation.
05–TX15	Calcareous fine grained sandstone; apparently Blanco Formation.
USGS–8	Caliche nodules in calcareous, fine-grained sandstone; apparently Blanco Formation.
04–TX15	Calcareous, fine-grained sandstone; apparently Blanco Formation.
USGS–7	Bedded caliche; forms caprock at upper surface of Ogallala Group in this area.
USGS–6	Massive, very fine grained caliche; in cap rock unit in uppermost Ogallala Group.
USGS–5	Weathered caliche with calcareous pebbles; in upper part of Ogallala Group.
01–TX15	Fine-grained sandstone; Couch Formation.
USGS–1	Calcareous, silty to very fine grained sandstone; Couch Formation.
03B–TX15	Fine-grained sandstone; Couch Formation.
USGS–3	Calcareous, very fine grained sandstone; Couch Formation.
USGS–4	Calcareous, very fine grained sandstone; Couch Formation.
USGS–2	Calcareous, clayey conglomerate with quartzite and chert pebbles in coarse- to fine-grained sand matrix; Couch Formation.
03A–TX15	Calcareous conglomerate; Couch Formation.
02A–TX15	Red mudstone and siltstone (red bed); upper Dockum Group.
02B–TX15	Greenish-gray mudstone and siltstone; upper Dockum Group. Contains 29 ppm Cu, 10 ppm Th.

[1]Maximum concentrations of some other elements in Blanco, Ogallala, and Couch Formation samples above: P, maximum of 0.06; As, all <30 ppm (limit of detection); Cu, 9 ppm; Mo, 6 ppm; Pb, 20 ppm; Th, 5 ppm.

sediments suggest that a calcrete uranium deposit may have occurred in this area of Yellow House Canyon.

Thick calcareous zones that form cap rock in this area revealed low and moderate values of uranium (samples USGS–7, USGS–6, and USGS–5 with values of 18, 71, and 3 ppm uranium, respectively). The calcareous horizons that form the cap rock are very likely caliche formed by pedogenic processes; however, the layer represented by sample USGS–6 does contain elevated uranium content (71 ppm uranium).

The Discovery of Uranium Deposits

Two radiometric anomalies identified by Kerr-McGee's regional airborne survey pointed them to areas of uranium mineralization exposed at the surface along Sulphur Springs Draw and Buzzard Draw. Extensive drilling of the two sites resulted in the discovery of shallow uranium deposits, which Kerr-McGee named the Sulphur Springs Draw and Buzzard Draw deposits (figs. 2 and 3; table 1).

Sulphur Springs Draw Deposit

The most significant cluster of radiometric anomalies identified by Kerr-McGee's regional ARDA survey pointed their researchers to the east side of Sulphur Springs Draw (figs. 2 and 3). Kerr-McGee geologists visited this area and found exposed in a trench "an area of obvious yellow carnotite mineralization in Ogallala caliche with outcrop samples assaying up to .05% U_3O_8" (quoted from a Kerr-McGee internal report). The center of this trench exposure is located at lat 32.44203ºN., long -101.87003ºW. The entire deposit lies within privately owned lands. A NURE flight line flown during the mid-1970s also detected a radiometric anomaly in the vicinity (Geodata International Inc., 1980; Hill and others, 2009). Existence of this exposure of uranium minerals (fig. 5) was briefly noted by Otton (1984) and Finch and others (1995), but neither mentioned Kerr-McGee's drilling program.

The mineralization exposed in this trench occurs as blotches of yellow and greenish-yellow uranium minerals, which coat grains, vugs, and surfaces of small fractures in a calcareous, very fine grained to fine-grained sandstone. Individual blotches of this mineralization are typically no more than 5 cm in diameter (fig. 5).

Company files indicate that Kerr-McGee drilled at least 669 holes into the Sulphur Springs Draw deposit (fig. 6). The holes were typically no more than 30 m in depth; each hole was logged by a gamma-radiation probe, and lithologies were recorded based on observations from drill core and cuttings (fig. 7). The subsurface extent of the buried uranium deposits is shown in figure 8. Its uranium resource estimate for this deposit totaled 2,311,259 short tons (2,096,774 t) of ore averaging 0.037 weight percent U_3O_8 (0.031 weight percent uranium) (table 1).

Kerr-McGee contracted a mineralogic analysis of one drill core from the deposit. This analysis found that the highest-grade intervals (0.021–0.274 weight percent U_3O_8) are associated with dolomite, illite, and montmorillonite. All samples of drill core that it analyzed, including ore and sub-ore rock, contained illite and montmorillonite. Calcite was identified in low-grade samples.

As described in company memoranda, the principal uranium mineral identified by Kerr-McGee's study of the drill core is carnotite, which occurs as grain coatings, vug fillings, and fracture coatings in the lacustrine rocks. One company memorandum suggests that tyuyamunite ($Ca(UO_2)_2(VO_4)_2 \cdot 5–8H_2O$) was also identified. In the Sulphur Springs Draw deposit, uranium mineralization occurs mainly in calcareous sandy siltstone and calcareous mudstone, but it does not appear to be confined to a specific horizon.

Uranium mineralization occurs just above the water table in calcareous siltstones and very fine grained sandstones. The highest radioactivity was found in calcareous mudstones and sandstones. The sediments hosting the deposit have a total thickness of as much as 30 m and rest directly on Triassic red-bed claystone and siltstone (fig. 7). The drill holes that transected the deposit bottomed in the upper 1 to 2 m of the Triassic strata.

U.S. Geological Survey Sampling Results from the Sulphur Springs Draw Deposit

A caliche zone as much as 6 m thick lies above the uranium-bearing lacustrine sediments and is the caprock unit of the draw. This calcareous cap rock is interpreted to be a pedogenic caliche based on the similarity of its characteristics to those of the caliche layers of the Blackwater Draw Formation in the area (fig. 4). For example, sampling by the USGS found that the caliche cap rock contained only 9 ppm uranium (sample 01G–SSD15, table 3).

Composite grab samples of rocks stained with yellow to greenish-yellow uranium mineralization were collected from exposed rocks in the trench on the western edge of the Sulphur Springs Draw deposit (fig. 5). These samples had uranium concentrations ranging from 100 to 245 ppm and vanadium concentrations ranging from 73 to 107 ppm (table 3). The host rocks, dominantly dolomitic, exhibit high magnesium and strontium contents (10–11 and 0.64–6.06 weight percent, respectively).

A scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectroscopy system (EDS) was used to examine uranium mineralization in two samples from Sulfur Springs Draw (samples 01A–SSD15 and 01B–SSD15, table 3). Secondary and backscattered electron images of the samples were acquired with a FEI Quanta 450 Field Emission Gun Scanning Electron Microscope operating at 15 kilovolts, approximately 2-nanoampere beam current. Energy-dispersive spectra were collected for 30 seconds live-count time with an EDAX Apollo X silicon drift detector. Semiquantitative EDS analyses of the uranium-bearing phases (fig. 9) identified ubiquitous blade-like crystals composed of strontium (Sr), uranium, and vanadium (approximately $(Sr,Ca)(UO_2)_2(VO_4)_2 \cdot 5–8H_2O$) intermixed with rhomboid grains with compositions suggesting carnotite

Figure 5. Examples of the yellow and greenish-yellow uranium mineralization exposed in a trench near the western edge of the Sulphur Springs Draw deposit. Mineralization occurs as thin coatings on calcareous, silty sandstone.

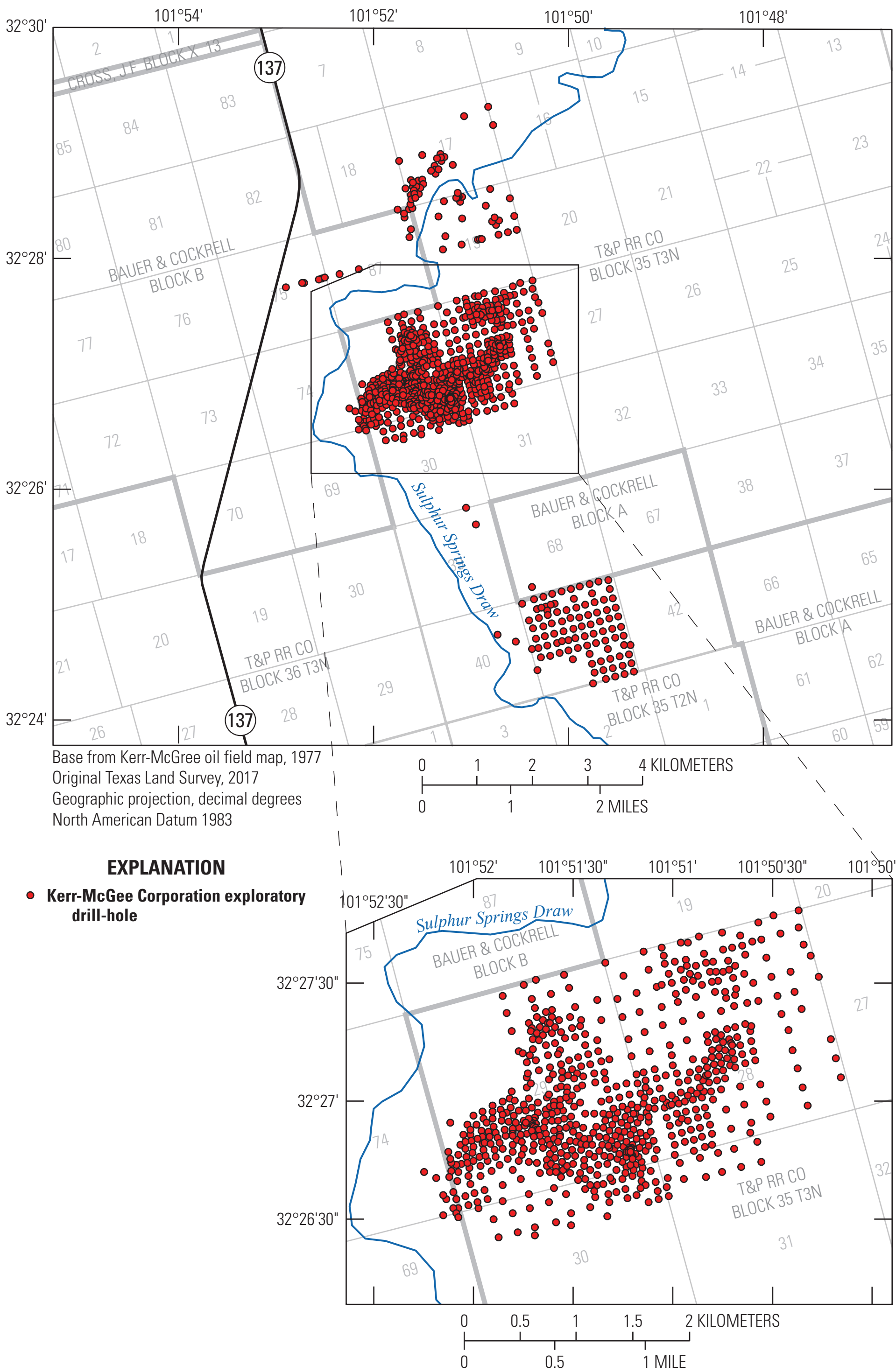


Figure 6. Drill-hole locations (red dots) of Kerr-McGee Corporation's exploratory drilling of the Sulphur Springs Draw deposit. Adapted from Kerr-McGee map dated January 1977.

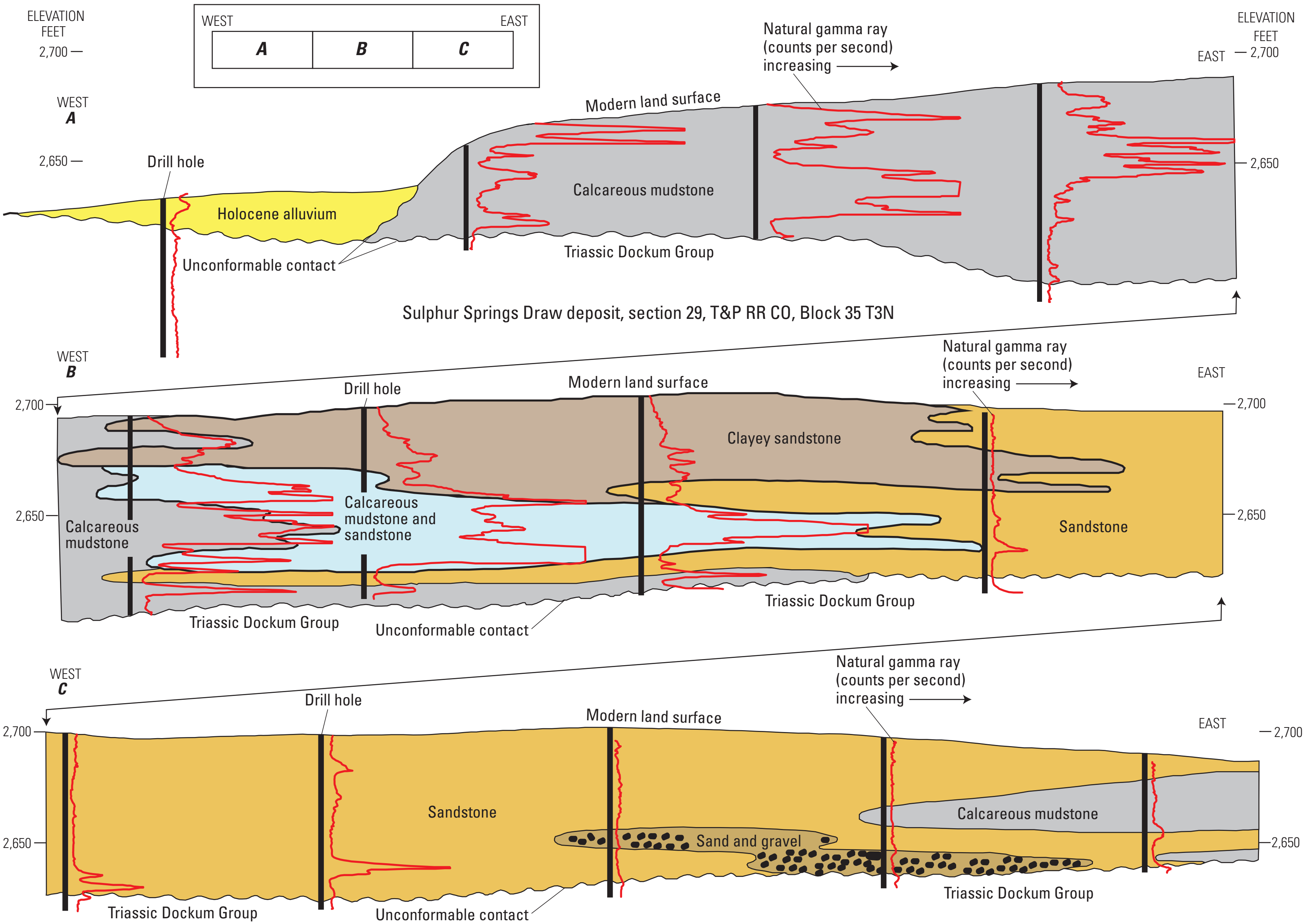


Figure 7. Cross section of the Sulphur Springs Draw deposit based on drilling results, showing lithologies and down-hole gamma-ray measurements (relative scale). Adapted from a hand-drawn cross section in the Kerr-McGee files.

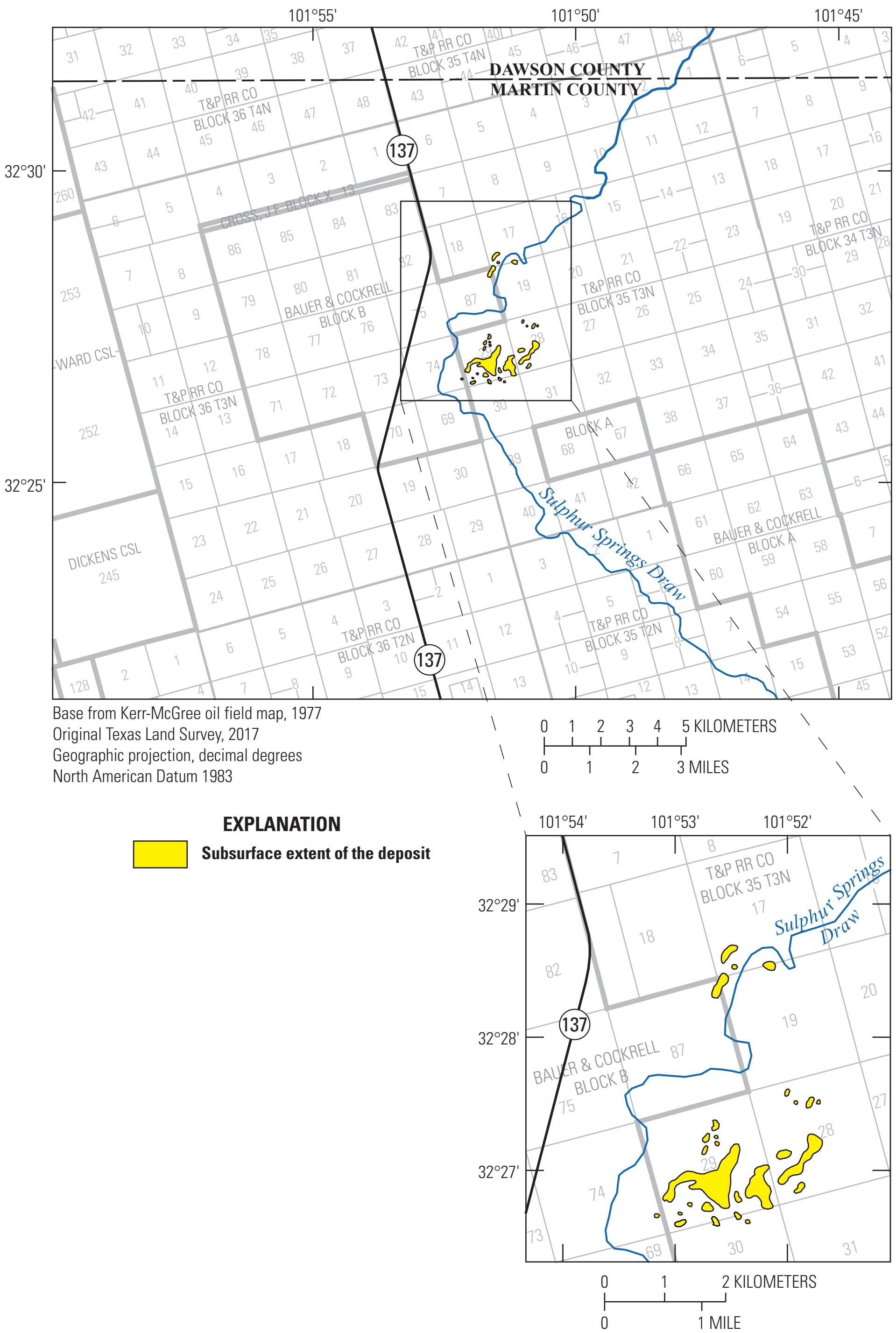


Figure 8. Index map of the Sulphur Springs Draw deposit showing the subsurface extent of the deposit (in yellow) based on drilling by Kerr-McGree Corporation and their interpretive map based on the drilling results.

Table 3. Concentrations of selected elements in samples collected in 2015 by this study from outcrops near the western edge of the Sulphur Springs Draw deposit, Martin County, Texas. Samples are presented in stratigraphic order with samples from the youngest strata at the top.

[Datum for latitude and longitude values is World Geodetic System 1984. Al, aluminum; As, arsenic; Ba, barium; Ca, calcium; Cu, copper; Fe, iron; K, potassium; Li, lithium; Mg, magnesium; Mn, manganese; Mo, molybdenum; P, phosphorus; Pb, lead; Sr, strontium; Th, thorium; U, uranium; V, vanadium; Zn, zinc; Zr, zirconium; wt%, weight percent; ppm, parts per million]

Sample	Latitude	Longitude	Concentration[1]														
			Al wt%	Ca wt%	Fe wt%	K wt%	Mg wt%	Mn wt%	As ppm	Ba ppm	Cu Ppm	Li ppm	Sr ppm	U ppm	V ppm	Zn ppm	Zr ppm
01G–SSD15	32.44203	–101.87003	0.83	20.8	0.37	0.4	3.95	0.004	<30	298	<5	28	3,796	9	22	<5	53.9
01A–SSD15	32.44203	–101.87003	0.55	17.2	0.28	0.3	9.99	0.017	41	539	<5	49	60,588	183	87	<5	23.6
01B–SSD15	32.44203	–101.87003	0.53	19.8	0.27	0.3	11.2	0.019	47	83	<5	47	6,376	136	73	<5	30.6
01C–SSD15	32.44203	–101.87003	0.49	19.5	0.26	0.2	11.2	0.02	46	246	<5	36	15,095	245	92	<5	21.8
01D–SSD15	32.44203	–101.87003	0.59	19	0.32	0.3	11.4	0.021	36	102	<5	57	9,996	217	107	11	18.1
01E–SSD15	32.44203	–101.87003	0.67	18.1	0.33	0.3	10.9	0.019	42	199	<5	45	8,710	100	74	5	34.2
01F–SSD15	32.44203	–101.87003	0.73	18.6	0.37	0.3	11	0.018	41	109	23	52	6,516	166	86	9	24.6
06–SSD15	32.44569	–101.86836	1.89	23.9	0.87	0.8	0.95	0.013	34	234	7	35	11,439	147	176	16	101

Sample descriptions

01G–SSD15	Ledge-forming caliche capping the lacustrine strata that host the uranium deposit.
01A–SSD15	Calcareous siltstone and very fine grained sandstone with visible greenish-yellow uranium minerals.
01B–SSD15	Calcareous siltstone and very fine grained sandstone with visible greenish-yellow uranium minerals.
01C–SSD15	Calcareous siltstone and very fine grained sandstone with visible greenish-yellow uranium minerals.
01D–SSD15	Calcareous siltstone and very fine grained sandstone with visible greenish-yellow uranium minerals.
01E–SSD15	Calcareous siltstone and very fine grained sandstone with visible greenish-yellow uranium minerals.
01F–SSD15	Calcareous siltstone and very fine grained sandstone with visible greenish-yellow uranium minerals.
06–SSD15	Calcareous, sandy mudstone exhibiting anomalously high radioactivity.

[1]Maximum concentrations of some other elements in the samples above: P, maximum of 0.03%; Mo, all <2 ppm; Pb, 10 ppm; Th, 3.7 ppm.

(approximately $K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$). Additional, more detailed analyses of these uranium minerals are underway. The uranium minerals occur with micritic dolomite, a late-stage strontium-calcium carbonate (fig. 9), celestine ($SrSO_4$), and grains of quartz, feldspars, and clay.

X-ray diffraction analyses of the yellow and greenish-yellow minerals also identified carnotite and an unspecific strontium-uranium-vanadium mineral (approximately $(H_2O)_2(UO_2)_2V_2O_8$), accompanied by dolomite, quartz, calcite, and celestine.

Carnotite is disseminated within the dolomicrite host, where it forms cements and fine veins. Later-stage crusts of carnotite, a strontium-uranium-vanadium mineral, celestine, and strontium-carbonate mineral were deposited in more porous areas of the dolomicrite host. The dolomite-rich matrix indicates that the host rocks could be deemed “dolocrete” rather than calcrete.

Preliminary uranium-series analyses of the unmineralized carbonate host, as well as carbonate associated with carnotite-rich crusts, were done as part of this study. The results lead to the interpretation that the carbonate host is the result of mixing in a two-component system, in which the lacustrine carbonate host was deposited prior to about 190 ka, and that solutions that resulted in precipitation of carnotite-rich crusts were introduced much later, during the Holocene (Hall and others, 2016). Initial $^{234}U/^{238}U$ activity ratios, which are inherited from solution at the time of mineral formation, are distinct for each end member and require the presence of two separate fluid sources. The possible implications of these findings are discussed in the Discussion section.

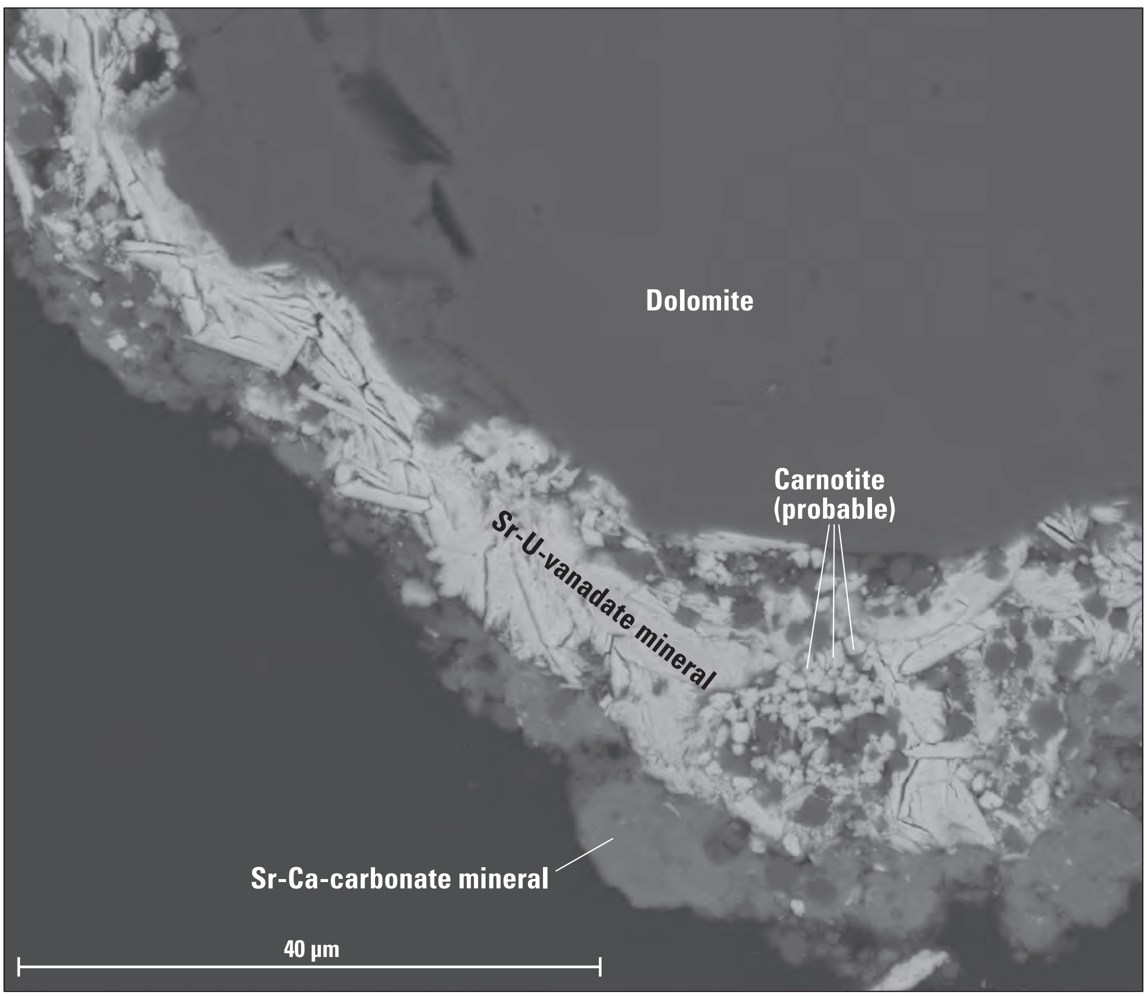


Figure 9. Scanning electron microscope image of uranium mineralization in the Sulphur Springs Draw deposit. Based on elemental compositions measured by an energy-dispersive X-ray spectroscopy system, the rhomboid crystals are likely carnotite, the blade-like crystals are a strontium-uranium-vanadium mineral, and the outer rim of alteration is a strontium-calcium carbonate. (Sr-U, strontium-uranium; Sr-Ca, strontium-calcium; µm, micrometer)

Buzzard Draw Deposit

The area that contains the Buzzard Draw deposit originally drew Kerr-McGee's interest because of a radiometric anomaly detected by an airborne survey, an oil-well gamma-ray log showing increased gamma counts in shallower horizons, and according to one memorandum, "a surface morphology suggestive of lacustrine deposits." Samples of well waters collected as a traverse across the area of the deposit exhibited uranium concentrations, for example, 35, 41, 150, 350, and 520 ppb. A sample of well water collected about 0.5 mile (0.8 km) from the subsequent drilling area contained 770 ppb uranium. Soils at the deposit site showed gamma counts of two to three times background values. A Kerr-McGee memorandum suggested that a surface show of uranium mineralization occurs at Buzzard Creek in Buzzard Draw, apparently along the eastern edge of the deposit. It reported that assays of this surface exposure revealed 0.003 to 0.013 percent U_3O_8. No exposures of this mineralization were found at the site of the Buzzard Draw deposit during USGS field research for this study. The land surface is today covered by cotton crops and by oil-well pads.

According to Kerr-McGee files, it drilled at least 305 holes into the Buzzard Draw deposit (figs. 10 and 11). As with the Sulphur Springs Draw deposit, the holes were typically no more than 30 m in depth; each hole was logged by a gamma-radiation probe, and lithologies were recorded based on observations from drill core and cuttings. A company memorandum noted that the Buzzard Draw deposit most likely extends farther to the north, but the landowner did not allow Kerr-McGee to explore that area. In total, Kerr-McGee estimated that the Buzzard Draw deposit contains 1,023,341 short tons (928,375 t) of ore with an average content of 0.047 weight percent U_3O_8 (0.04 weight percent uranium) (table 1).

Uranium mineralization in the Buzzard Draw deposit mainly occurs in a fine- to medium-grained silty, clayey sandstone unit that contains scattered quartz pebbles. Based on company reports, the uranium-rich zone consistently occurs at or near the contact with underlying Triassic red beds of the Dockum Group.

Ore Calculations

Kerr-McGee's uranium resource calculations for the two deposits (table 1) included resources in the measured, indicated, and inferred categories. Resources classified as potential were not included. The two deposits were drilled on a spacing of 150 ft (46 m) or less. Thus, the resource figures presented by Kerr-McGee have a relatively high level of confidence.

Kerr-McGee's resources were calculated for deposits measuring at least 3 ft (0.9 m) thick and containing 0.030 weight percent U_3O_8. Individual intercepts frequently exceeded 0.10 percent U_3O_8, and the bulk of the resource is present in intervals averaging less than 0.060 percent U_3O_8. All resource calculations applied a density of 15 cubic feet per short ton, which was determined by bulk sampling.

Kerr-McGee calculated that the combined resources of the Sulphur Springs Draw and Buzzard Draw deposits total about 3,025,150 metric tons of ore at an average grade of about 0.04 weight percent U_3O_8 (table 1). For comparison, Cameco Corporation has reported for its Yeelirrie property in West Australia a total measured and indicated resources of 39,351,000 metric tons of ore at an average grade of 0.12 to 0.16 percent U_3O_8 (as of December 31, 2016; Cameco Corporation, 2016).

Additional Exploration in the Area

During the 1970s, Kerr-McGee drilled hundreds of exploratory holes in the area near the Sulphur Springs Draw and Buzzard Draw deposits (fig. 12). However, aside from uranium mineralization near the Sulphur Springs Draw and Buzzard Draw deposits (figs. 8 and 11), Kerr-McGee did not find other uranium deposits in the area. Company memoranda suggest that Kerr-McGee's exploration program in this region ended around 1981.

Kerr-McGee Corporation's Cost-of-Production Analysis

In 1981, Kerr-McGee conducted an economic analysis to estimate the total costs to mine and produce yellowcake (milled uranium oxide) from the uranium resources at the Sulphur Springs Draw and Buzzard Draw deposits. At that time, the company leased properties at the two deposits on privately owned fee lands. The shallow depth of these deposits made them potentially attractive for small-scale open-pit mining. The researchers concluded that the remoteness of the properties in relation to existing uranium ore-processing facilities meant the ore would need to be upgraded (through removal of sands and silt) to make shipping for milling cost effective. Its analysis included cost estimates for stripping and mining, onsite upgrading of the ore (by hydro-centrifuge), hauling, milling (to 95 percent recovery), development (infill drilling, permitting, and other factors), and equipment (hydro-centrifuge equipment, onsite offices, facilities, vehicles, and miscellaneous), plus general and administrative expenses. Its estimated total cost of production for the two deposits, including all steps from mining to yellowcake production, was $29.07 per pound of U_3O_8 (calculated February 1981, as reported in an internal company memorandum).

This cost estimate appears to have ended Kerr-McGee's interest in the Sulphur Springs Draw and Buzzard Draw deposits, as well as the corporation's interest in exploring further for similar deposits in the Southern High Plains region. In its analyses, the researchers suggested that production from the mines would begin in 1985. From a spot market price of $40 per pound of U_3O_8 in 1980, the price fell to below $20 per pound of U_3O_8 in 1981 and continued to stay below this value throughout the 1980s. Thus, it appears that the mining of these deposits during the 1980s would have been an uneconomic proposition for the company.

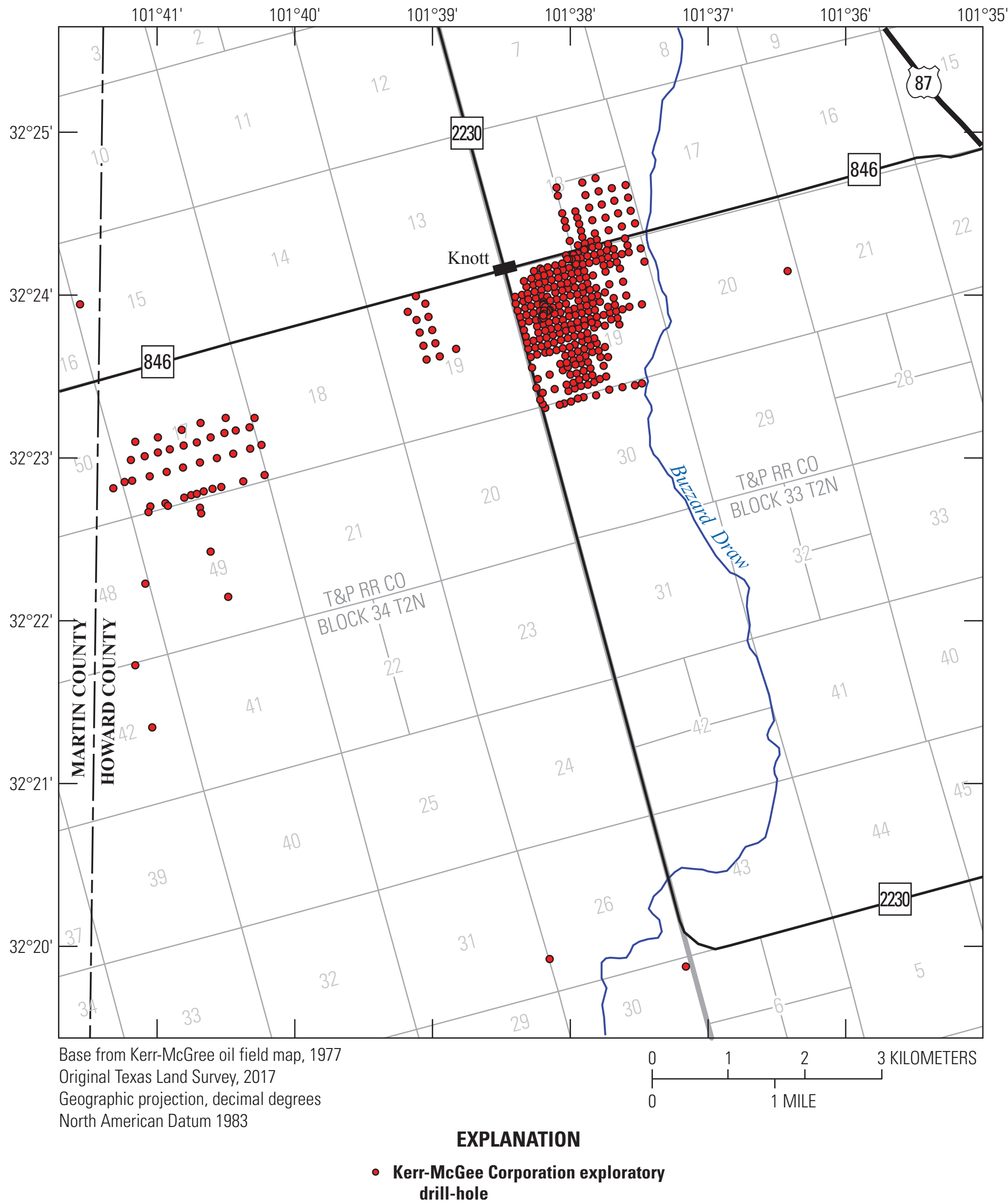


Figure 10. Drill-hole locations (red dots) of Kerr-McGee Corporation's exploratory drilling of the Buzzard Draw deposit. Adapted from Kerr-McGee map dated November 1978.

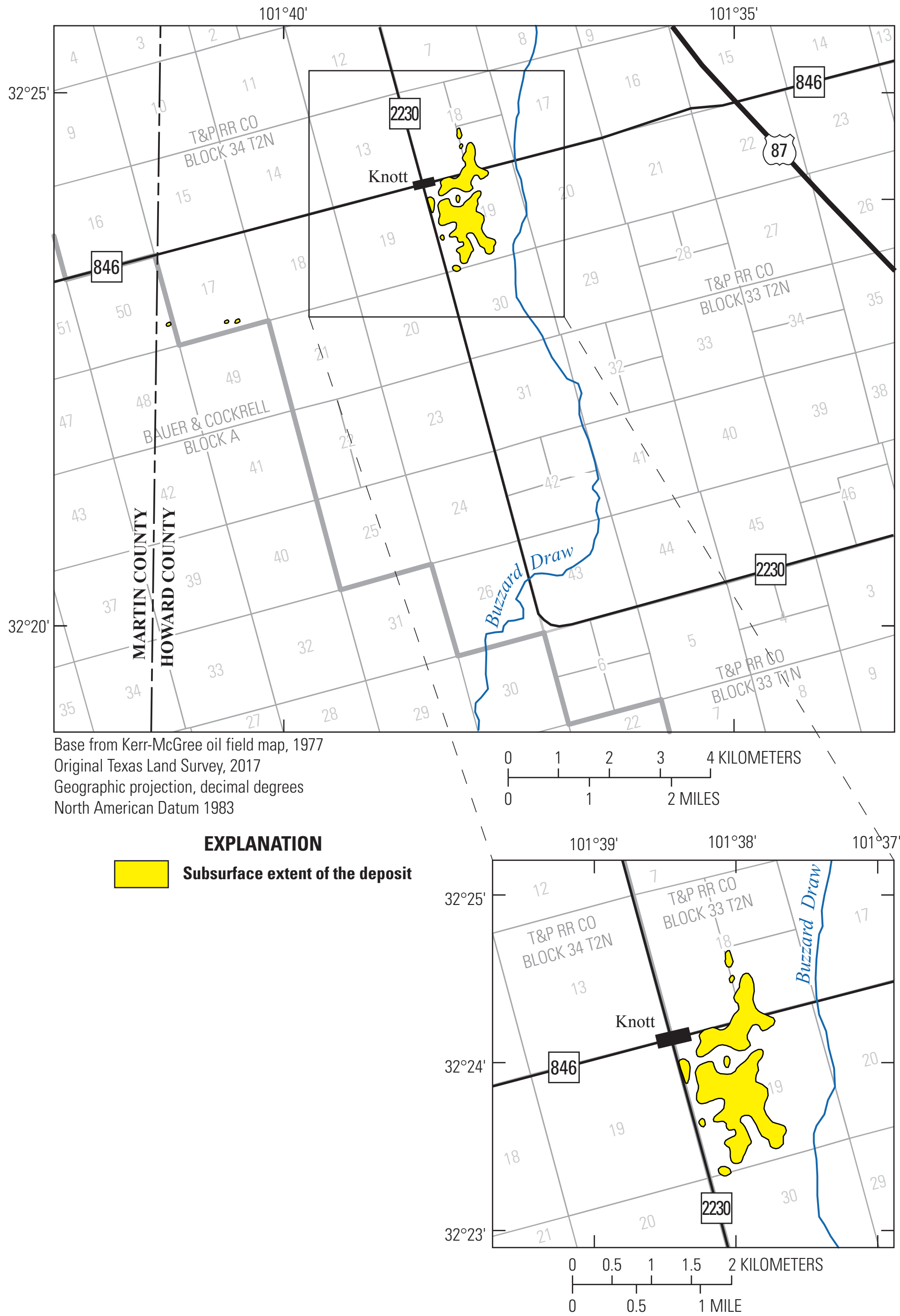


Figure 11. Index map of the Buzzard Draw deposit showing the subsurface extent of the deposit (in yellow) based on drilling by Kerr-McGee Corporation.

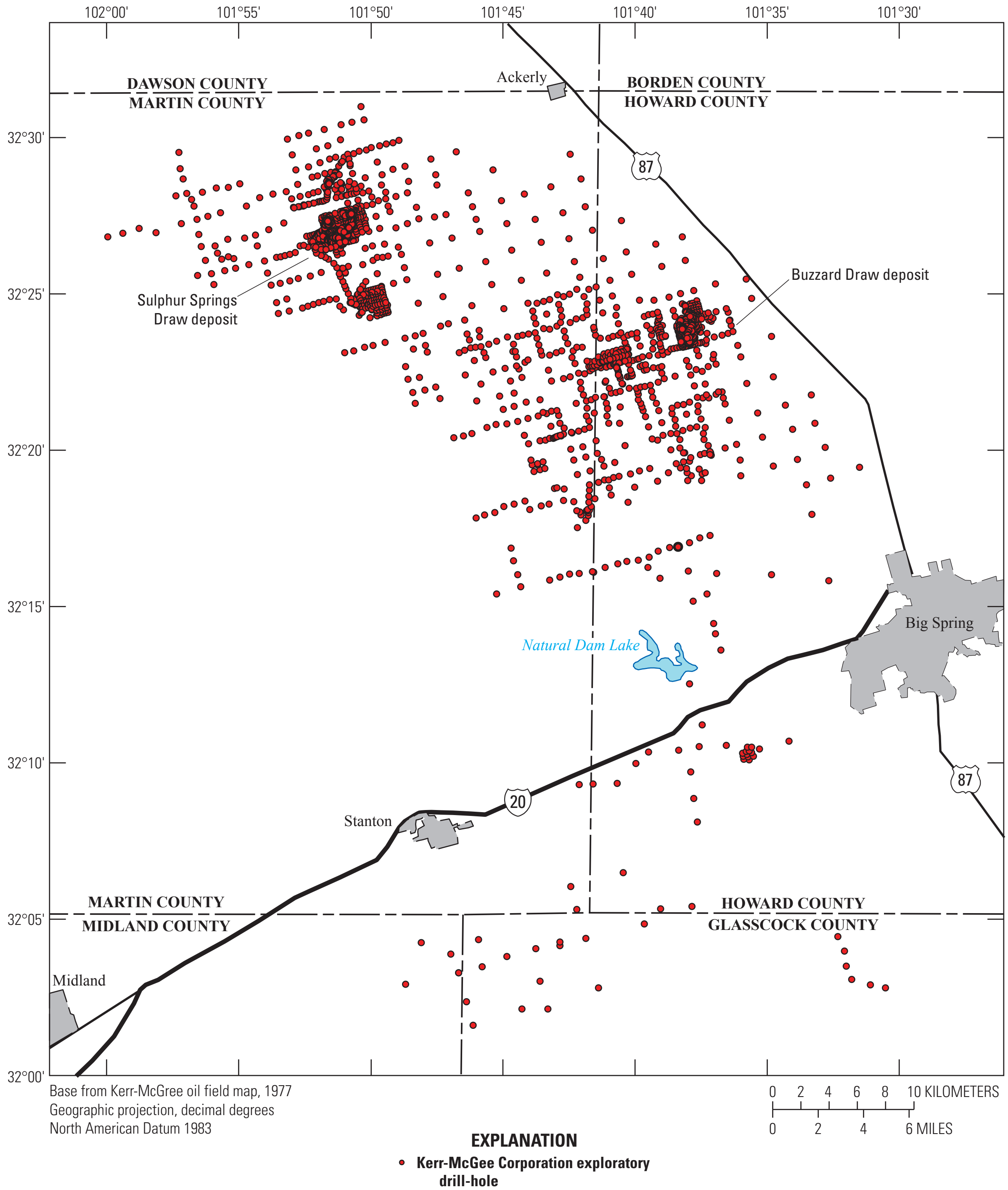


Figure 12. Drill-hole locations (red dots) of Kerr-McGee Corporation's 1970s exploratory drilling program in the Southern High Plains region of Texas.

Discussion

Because the Kerr-McGee records have been well archived, the public is now aware of two near-surface uranium deposits within the Southern High Plains of west Texas. These deposits are calcrete uranium deposits, a deposit type not previously reported in the United States. The west Texas deposits are smaller in size and of lower uranium grade than the classic calcrete uranium deposits of Yeelirrie in Western Australia (Carlisle, 1978; Butt and others, 1984; Cameron, 1984; Cavaney, 1984; Heath and others, 1984), and they differ in some details, but they do share several geologic similarities For example, the Pleistocene paleogeography and depositional environments of the Southern High Plains are generally similar to those in which the West Australia uranium deposits were formed. Also, they are similar in (1) the principal uranium ore mineral, carnotite; (2) the host rocks, calcareous lacustrine sediments (calcrete); (3) the climatic conditions during deposition, arid to semiarid; (4) the geographic setting, an inland setting with a low regional gradient; and (5) the depths to the ore zones, shallow (the deposits often occurring within 10–20 m of the ground surface).

The discovery of the west Texas deposits suggests that other uranium deposits of this type can exist in the Southern High Plains and could be concealed beneath the widespread cover of the Blackwater Formation. The discovery of additional deposits by Kerr-McGee's exploration project could have been limited by (1) the spacing of the airborne flight lines (exact flight line spacing is not known, but some deposits may not have been crossed by a flight line); (2) the shallow depth of penetration by airborne radiometric surveys (they cannot detect anomalous radioactivity beneath as little as 0.5 m of cover such as soil or loess); (3) the possibility of difficulties obtaining land access for follow-up ground surveys; and (4) a sparse distribution of water wells for chemical analyses in some areas.

Because a deposit model that explains the genesis of these uranium deposits could aid in the discovery of additional deposits in the region, one was developed as part of this study. This deposit model includes the characteristics, depositional setting, and age of the host calcrete strata; the source(s) of the uranium and vanadium; mechanism(s) of uranium-vanadium precipitation; and the age(s) of the uranium-vanadium mineralization.

Host Calcrete Strata

Several pieces of evidence suggest that the host strata for the uranium mineralization are sediments deposited in Pleistocene saline lakes. Micritic dolomite is the principal mineral, accompanied by considerable celestine ($SrSO_4$); these are common mineral precipitates in saline lakes. The bowl shape of the calcrete strata fits the typical morphology of deposits emplaced in a shallow lacustrine setting, which would be a few kilometers in diameter and filled with sediments as much as 30 m thick. The paleogeology, paleogeography, and paleoclimate of the Southern High Plains indicate that saline lakes existed in the region during interglacial periods of the Pleistocene, as represented by strata of the Pleistocene-age Tahoka Formation and extinct Pleistocene Lake Lomax, the basin of which is located about 10–20 km to the south of the uranium deposits (fig. 3) (Frye and Leonard, 1968). The age of the host calcrete at the Sulphur Springs Draw deposit is provisionally dated at about 190 ka, based on preliminary uranium-series dating of the unmineralized micritic dolomite matrix (Hall and others, 2016). However, the presence of the Lava Creek B ash layer (631±4 ka, $^{40}Ar/^{39}Ar$ method, Fish Canyon standard, 28.17 Ma, Matthews and others, 2015) in strata immediately adjacent to the Sulphur Springs Draw deposit strongly suggests that strata of the Tule Formation host the uranium deposit. The 190 ka age for the dolomite matrix may indicate a younger fluid event that recrystallized the host rocks.

Sources and Mechanisms of the Uranium-Vanadium Mineralization

The most expedient source of uranium and vanadium to these deposits is the Dockum Group strata that lie beneath and in direct contact with the calcrete strata. The Dockum Group in the region locally contains numerous uranium occurrences and small deposits (Hayes, 1956; Finch, 1975). For example, small uranium deposits occur in the Dockum Group in Garza County, about 100 km to the northeast of the Sulphur Springs Draw and Buzzard Draw deposits. The Dockum Group deposits contain uranium-vanadium mineralization in the form of tyuyamunite and metatyuyamunite.

In addition to the Dockum Group minerals, an ash bed now recognized in strata immediately adjacent to the Sulphur Springs Draw deposit offers another potential source of uranium. As described in the "Pleistocene Lacustrine Deposits that Host the Uranium Deposits" section, the USGS Tephrochronology Project determined that this ash was Lava Creek B with an age of 631±4 ka ($^{40}Ar/^{39}Ar$ method, Fish Canyon standard, 28.17 Ma, Matthews and others, 2015); thus, its eruptive source was from the Yellowstone National Park region of Wyoming. The Lava Creek B ash in this region occurs in the upper part of the Tule Formation (middle Pleistocene), suggesting that strata of the Tule Formation are the host for the Sulphur Springs Draw uranium deposit. Geochemical analyses of a hand sample of this ash-bearing layer found a uranium content of 6.9 ppm.

Other traditional sources of uranium and vanadium, such as igneous and metamorphic rocks, form the basement in the Southern High Plains and are covered by more than 2 km of sediment. The nearest surface exposures of basement rocks occur hundreds of kilometers from the uranium deposits.

Uranium-vanadium minerals may be the least soluble of uranyl minerals and are thought to most likely form when dissolved uranium comes in contact with waters containing dissolved vanadate ions (Finch and Murakami, 1999). Vanadium in reduced form is often found in clay-rich rocks (mudstones and shales). Most reported occurrences of carnotite are as oxidation products of reduced U(IV) minerals and associated reduced V(III)-bearing clays. Thus, the source of uranium and vanadium for the west Texas deposits (carnotite-group minerals) may be the chemically reduced, greenish-gray, clayey strata of the underlying Dockum Group. Upon oxidation of these strata, uranium and (or) vanadium can be mobilized upward from Dockum Group mudstones into the overlying Pleistocene sediments.

Elevated concentrations of uranium, and associated radioactive daughter products such as radon and radium, are common in shallow groundwaters of the Southern High Plains, particularly in saline lake basins, based on many analyses of well waters in the region (Bartolino, 1991; Hopkins, 1993; Hudak, 2005; Scanlon and others, 2009; Ranalli and Yager, 2016). Hudak (2005) collected 48 samples of well waters from the Dockum aquifer and found that 17 percent of the samples exceeded the drinking-water standards for alpha radioactivity. He concluded, "Uranium deposits in sandstone and shale of the Dockum aquifer, and in calcrete and silcrete of the Ogallala aquifer, and overlying lacustrine sediments, likely influence radioactivity patterns observed in this study" (Hudak, 2005, p. 283). Scanlon and others (2009) report that dissolved vanadium can also be anomalously high in saline groundwaters of the Southern High Plains aquifer.

Ranalli and Yager (2016) used the USGS computer software code PHREEQC (Parkhurst and Appelo, 1999) to model the potential for precipitation of carnotite from water that is sufficiently saturated in uranium and vanadium concentrations through progressive evaporation of groundwaters typical of the Southern High Plains. Some of the groundwaters were tapped by wells in the area of the uranium deposits. They input the chemistry of shallow groundwaters from wells in the Ogallala aquifer, systematically varied the concentration of uranium in groundwater, and modeled the progressive evaporation of the water while variably opening and closing the system to CO_2. The calculations found that unusually high initial concentrations of total dissolved uranium and vanadium in the groundwater were not required to achieve carnotite saturation. Rather, "in groundwater that achieved carnotite saturation the [initial] concentration of uranium ranged from 2.12 to 21.9 µg/L with a median concentration of 9.14 µg/L and the concentration of vanadium ranged from 12.8 to 118 µg/L with a median concentration of 29.3 µg/L" (Ranalli and Yager, 2016, p. 130; µg/L, microgram per liter). Their calculations indicated that carnotite saturation could be achieved through the evaporation of a subset of groundwaters under three conditions: (1) the initial water chemistry was dominated by Ca-Mg-SO_4 or Ca-Mg bicarbonate; (2) the system was open to CO_2; and (3) following the precipitation of calcite, the concentration of calcium exceeded carbonate alkalinity. These boundary conditions could have occurred within saline lakes in this region during the Pleistocene.

Relative Ages of the Uranium-Vanadium Mineralization

This study included mineralogical analyses of uranium-vanadium mineralization in outcrop samples taken from the trench exposure at the Sulphur Springs Draw deposit (Hall and others, 2016). The analyses used a scanning electron microscope equipped with energy-dispersive X-ray spectroscopy. In addition, six subsamples from two lacustrine calcrete specimens (one unmineralized and one with carnotite coating fracture surfaces) were analyzed for uranium-series isotopes by thermal ionization mass spectrometry. As noted in the "Sulphur Springs Draw Deposit" section, results imply that finely disseminated uranium mineralization in the fine-grained dolomite matrix formed prior to about 190 ka and secondary uranium-vanadium mineralization was introduced much later (Holocene). Paragenetically early carnotite is disseminated in the dolomicrite host in small pores and is present as coatings on dolomite grains and on thin veinlets. Later-stage crusts composed of carnotite, a uranium-strontium-vanadium mineral, celestite, and a strontium-calcium carbonate were deposited in vuggy areas and on thin fracture surfaces. The paragenetically late crusts of a uranium-vanadium mineral (carnotite) and a uranium-strontium-vanadium mineral may have formed as recently as about 5 ka based on interpretations of preliminary uranium-series dating. Differences in initial $^{234}U/^{238}U$ activity ratios for the older dolomicrite matrix and the younger uranium-vanadium crusts indicate two distinct fluid sources. These data imply that the host micritic dolomite may represent the deposition of carbonate in the saline lake sediments (or relatively soon thereafter) during marine-isotope stage 7 interglacial conditions. The much younger uranium-vanadium and uranium-vanadium-strontium mineralization that formed crusts could represent recent remobilization of older uranium and vanadium concentrates from underlying sediments and (or) a separate fluid influx that brought additional uranium and vanadium to the system.

Conclusions

Further consideration of these factors will produce a refined deposit model that can indicate the most favorable areas for calcrete uranium deposits similar to those at Sulphur Springs Draw and Buzzard Draw. Because the extensive cover of the Blackwater Draw Formation complicates the use of standard regional reconnaissance techniques, such as airborne radiometric surveys, a deposit model could aid in the search for potential uranium deposits. Given the preliminary deposit model discussed in this report, it is likely that areas defined as favorable by a refined deposit model will be along the margins of "draws" that incise the plains, as exemplified by Kerr-McGee's two discoveries.

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